Self-interacting dark matter and Higgs bosons in the $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ model with right-handed neutrinos

Hoang Ngoc Long[a,b] **and Nguyen Quynh Lan**[a]

[a] *Institute of Physics, NCST, P. O. Box 429, Bo Ho, Hanoi 10000, Vietnam*
[b] *The Abdus Salam International Centre for Theoretical Physics, Trieste 34014, Italy.*

Abstract

We investigate the possibility that dark matter could be made from CP-even and CP- odd Higgs bosons in the $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ (3-3-1) model with right-handed neutrinos. This self-interacting dark matters are stable without imposing of new symmetry and should be weak-interacting.

PACS number(s): 95.35.+d, 12.60.Fr, 14.80.Cp
Keywords: Dark Matter, scalar particles

It is an amazing fact that even as our understanding of cosmology progresses by leaps and bounds, we remain almost completely ignorant about the nature of most of the matter in the universe [1]. Cosmological models with a mixture of roughly 35% collisionless cold dark matter such as axions, WIMPs, or any other candidate interacting through the weak and gravitational forces only, and 65% vacuum energy or quintessence match observation of the cosmic microwave background and large scale structure on extra-galactic scales with remarkable accuracy [2, 3]. It is known that only a fraction of the dark matter can be made of ordinary baryons and its enormous amount has unknown, nonbaryonic origin [4]. The nature of dark matter is still a challenging question in cosmology.

Until a few years ago, the more satisfactory cosmological scenarios were those ones composed of ordinary matter, cold dark matter and a contribution associated with the cosmological constant. To be consistent with inflationary cosmology, the spectrum of density fluctuations would be nearly scale-invariant and adiabatic. However, in recent years it has been pointed out that the conventional models of collisionless cold dark matter lead to problems with regard to galactic structures. They were only able to fit the observations on large scales ($\gg 1$ Mpc). Also, N-body simulations in these models result in a central singularity of the galactic halos [5] with a large number of sub-halos [6], which are in conflict with astronomical observations. A number of other inconsistencies are discussed in Refs. [7, 8]. Thus, the cold dark matter model is not able to explain observations on scales smaller than a few Mpc.

However, it has recently been shown that an elegant way to avoid these problems is to assume the so called *self-interacting dark matter* [9]. One should notice that, in spite of all, self-interacting models lead to spherical halo centers in clusters, which is not in

agreement with ellipsoidal centers indicated by strong gravitational lens observations [10] and by Chandra observations [11].

However, self-interacting dark matter models are self-motivated as alternative models. It is a well-accepted fact that the plausible candidates for dark matter are elementary particles. The key property of these particles is that, they must have a large scattering cross-section and negligible annihilation or dissipation. The Spergel-Steinhard model has motivated many follow-up studies [4, 12, 13]. Several authors have proposed models in which a specific scalar singlet that satisfies the self-interacting dark matter properties is introduced in the standard model (SM) in an *ad hoc* way [4, 13].

The SM offers no options for dark matter. The first gauge model for SIDM were found by Fregolente and Tonasse [14] in the 3-3-1 model. It is to be noted that in the model considered in [14] to keep the Higgs sector with three triplets one has to propose an existence of *exotic leptons*. The 3-3-1 models were proposed with an independent motivation [15]. These models have the following intriguing features such as the models are anomaly free only if the number of families N is a multiple of three. If further one adds the condition of QCD asymptotic freedom, which is valid only if the number of families of quarks is to be less than five, it follows that N is equal to 3.

A subject that has not been given much attention by particle physicists in the past, could prove to be a remarkable powerful and precise probe of the properties of dark matter.

The aim of this paper is to show that the 3-3-1 model with right-handed (RH) neutrinos [16] contains such self-interacting dark matter.

To frame the context, it is appropriate to recall briefly some relevant features of the 3 - 3 - 1 model with RH neutrinos [16]. In this model the leptons are in triplets, and the third member is a RH neutrino:

$$f^a_L = (\nu^a_L, e^a_L, (\nu^c_L)^a)^T \sim (1, 3, -1/3), e^a_R \sim (1, 1, -1). \tag{1}$$

The first two generations of quarks are in antitriplets while the third one is in a triplet:

$$Q_{iL} = (d_{iL}, -u_{iL}, D_{iL})^T \sim (3, \bar{3}, 0), \tag{2}$$

$$u_{iR} \sim (3, 1, 2/3), d_{iR} \sim (3, 1, -1/3), D_{iR} \sim (3, 1, -1/3), \ i = 1, 2,$$

$$Q_{3L} = (u_{3L}, d_{3L}, T_L)^T \sim (3, 3, 1/3), \tag{3}$$

$$u_{3R} \sim (3, 1, 2/3), d_{3R} \sim (3, 1, -1/3), T_R \sim (3, 1, 2/3).$$

The charged gauge bosons are defined as

$$\begin{aligned} \sqrt{2}\, W^+_\mu &= W^1_\mu - iW^2_\mu, \sqrt{2}\, Y^{-}_\mu = W^6_\mu - iW^7_\mu, \\ \sqrt{2}\, X^o_\mu &= W^4_\mu - iW^5_\mu. \end{aligned} \tag{4}$$

The *physical* neutral gauge bosons are again related to Z, Z' through the mixing angle ϕ. The symmetry breaking can be achieved with just three $\mathrm{SU}(3)_L$ triplets

$$\begin{aligned} \chi &= \left(\chi^0, \chi^-, \chi^{,0}\right)^T \sim (1, 3, -1/3), \\ \rho &= \left(\rho^+, \rho^0, \rho^{,+}\right)^T \sim (1, 3, 2/3), \\ \eta &= \left(\eta^0, \eta^-, \eta^{,0}\right)^T \sim (1, 3, -1/3), . \end{aligned} \tag{5}$$

The necessary VEVs are

$$\langle\chi\rangle = (0, 0, \omega/\sqrt{2})^T,\ \langle\rho\rangle = (0, u/\sqrt{2}, 0)^T,\ \langle\eta\rangle = (v/\sqrt{2}, 0, 0)^T. \tag{6}$$

After symmetry breaking the gauge bosons gain masses

$$m_W^2 = \frac{1}{4}g^2(u^2+v^2),\ M_Y^2 = \frac{1}{4}g^2(v^2+\omega^2), M_X^2 = \frac{1}{4}g^2(u^2+\omega^2). \tag{7}$$

Eqn.(7) gives us a relation

$$v_W^2 = u^2 + v^2 = 246^2 \ \ \mathrm{GeV}^2. \tag{8}$$

In order to be consistent with the low energy phenomenology we have to assume that $\langle\chi\rangle \gg \ \langle\rho\rangle,\ \langle\eta\rangle$ such that $m_W \ll M_X, M_Y$.

The symmetry-breaking hierarchy gives us splitting on the bilepton masses [17]

$$|M_X^2 - M_Y^2| \leq m_W^2. \tag{9}$$

Our aim in this paper is to show that the 3-3-1 model with RH neutrinos furnishes a good candidate for (self-interacting) dark matter. The main properties that a good dark matter candidate must satisfy are stability and neutrality. Therefore, we go to the scalar sector of the model, more specifically to the neutral scalars, and we examine whether any of them can be stable and in addition whether they can satisfy the self-interacting dark matter criterions [9]. In addition, one should notice that such dark matter particle must not overpopulate the Universe. On the other hand, since our dark matter particle is not imposed arbitrarily to solve this specific problem, we must check that the necessary values of the parameters do not spoil the other bounds of the model.

Under assumption of the discrete symmetry $\chi \to -\chi$, the most general potential can then be written in the following form [18]

$$\begin{aligned} V(\eta,\rho,\chi) &= \mu_1^2\eta^+\eta + \mu_2^2\rho^+\rho + \mu_3^2\chi^+\chi + \lambda_1(\eta^+\eta)^2 + \lambda_2(\rho^+\rho)^2 + \lambda_3(\chi^+\chi)^2 \\ &+ (\eta^+\eta)[\lambda_4(\rho^+\rho) + \lambda_5(\chi^+\chi)] + \lambda_6(\rho^+\rho)(\chi^+\chi) + \lambda_7(\rho^+\eta)(\eta^+\rho) \\ &+ \lambda_8(\chi^+\eta)(\eta^+\chi) + \lambda_9(\rho^+\chi)(\chi^+\rho) + \lambda_{10}(\chi^+\eta + \eta^+\chi)^2. \end{aligned} \tag{10}$$

We rewrite the expansion of the scalar fields which acquire a VEV:

$$\eta^o = \frac{1}{\sqrt{2}}\left(v + \xi_\eta + i\zeta_\eta\right);\ \rho^o = \frac{1}{\sqrt{2}}\left(u + \xi_\rho + i\zeta_\rho\right);\ \chi^o = \frac{1}{\sqrt{2}}\left(w + \xi_\chi + i\zeta_\chi\right). \tag{11}$$

For the prime neutral fields which do not have VEV, we get analogously:

$$\eta'^o = \frac{1}{\sqrt{2}}\left(\xi'_\eta + i\zeta'_\eta\right);\ \chi'^o = \frac{1}{\sqrt{2}}\left(\xi'_\chi + i\zeta'_\chi\right). \tag{12}$$

Requiring that in the shifted potential V, the linear terms in fields must be absent, we get in the tree level approximation, the following constraint equations:

$$\begin{aligned} \mu_1^2 + \lambda_1 v^2 + \frac{1}{2}\lambda_4 u^2 + \frac{1}{2}\lambda_5 w^2 &= 0, \\ \mu_2^2 + \lambda_2 u^2 + \frac{1}{2}\lambda_4 v^2 + \frac{1}{2}\lambda_6 w^2 &= 0, \\ \mu_3^2 + \lambda_3 w^2 + \frac{1}{2}\lambda_5 v^2 + \frac{1}{2}\lambda_6 u^2 &= 0. \end{aligned} \tag{13}$$

Since dark matter has to be neutral, then we consider only neutral Higgs sector. In the $\xi_\eta, \xi_\rho, \xi_\chi, \xi'_\eta, \xi'_\chi$ basis the square mass matrix, after imposing of the constraints (13), has a quasi-diagonal form as follows:

$$M_H^2 = \begin{pmatrix} M_{3H}^2 & 0 \\ 0 & M_{2H}^2 \end{pmatrix}, \tag{14}$$

where

$$M_{3H}^2 = \frac{1}{2}\begin{pmatrix} 2\lambda_1 v^2 & \lambda_4 vu & \lambda_5 vw \\ \lambda_4 vu & 2\lambda_2 u^2 & \lambda_6 uw \\ \lambda_5 vw & \lambda_6 uw & 2\lambda_3 w^2 \end{pmatrix}, \tag{15}$$

and

$$M_{2H}^2 = \left(\frac{\lambda_8}{4} + \lambda_{10}\right)\begin{pmatrix} w^2 & vw \\ vw & v^2 \end{pmatrix}. \tag{16}$$

The above mass matrix shows that the prime fields mix themselves but do not mix with others. In the limit

$$\lambda_1 v,\ \lambda_2 u,\ \lambda_4 u \ll \lambda_5 w,\ \lambda_6 w, \tag{17}$$

we obtained physical eigenstates $H_1(x)$ and $\sigma(x)$

$$\begin{pmatrix} H_1(x) \\ \sigma(x) \end{pmatrix} = \frac{1}{(\lambda_5^2 v^2 + \lambda_6^2 u^2)^{1/2}}\begin{pmatrix} \lambda_6 u & -\lambda_5 v \\ \lambda_5 v & \lambda_6 u \end{pmatrix}\begin{pmatrix} \xi_\eta \\ \xi_\rho \end{pmatrix}, \tag{18}$$

with masses [18]

$$m_{H_1}^2 \approx \frac{v^2}{4\lambda_6}(2\lambda_1\lambda_6 - \lambda_4\lambda_5) \approx \frac{u^2}{4\lambda_5}(2\lambda_2\lambda_5 - \lambda_4\lambda_6), \tag{19}$$

$$m_\sigma^2 \approx \frac{1}{2}\lambda_1 v^2 + \frac{\lambda_4\lambda_6 u^2}{4\lambda_5} \approx \frac{1}{2}\lambda_2 u^2 + \frac{\lambda_4\lambda_5 v^2}{4\lambda_6}. \tag{20}$$

Eqs. (19) and (20) also give us relations among coupling constants and VEVs. Another massive physical state H_3 with mass:

$$m_{H_3}^2 \approx -\lambda_3 w^2. \tag{21}$$

The scalar $\sigma(x)$ is the one that we can identify with the SM Higgs boson [18].

In the approximation $w \gg v$, mass matrix M_{2H}^2 gives us one Goldstone ξ'_χ and one physical massive field ξ'_η with mass

$$m_{\xi'_\eta}^2 = -\left(\frac{\lambda_8}{4} + \lambda_{10}\right) w^2. \tag{22}$$

In the pseudoscalar sector, we have three Goldstone bosons which can be identified as follows: $G_2 \equiv \zeta_\eta,\ G_3 \equiv \zeta_\rho,\ G_4 \equiv \zeta_\chi$ and in the $\zeta'^o_\eta, \zeta'^o_\chi$ basis

$$M_{2A}^2 = \left(\frac{\lambda_8}{4} + \lambda_{10}\right)\begin{pmatrix} w^2 & vw \\ vw & v^2 \end{pmatrix}. \tag{23}$$

We easily get one Goldstone G'_5 and one massive pseudoscalar boson ζ'_η with mass

$$m^2_{\zeta'_\eta} = -\left(\frac{\lambda_8}{4} + \lambda_{10}\right) w^2. \tag{24}$$

It is to be emphasized that, both ξ'_η and ζ'_η are in an singlet of the $SU(2)$. Therefore they do not interact with the SM gauge bosons $W^\pm, Z^0$ and γ. Unlike the 3-3-1 model considered in [14], here we have two fields which can be considered as dark matter.

To get the interaction of dark matter to the SM Higgs boson, we consider the following relevant parts

$$\begin{aligned} L_{int}(\sigma,\zeta_\eta) &= \frac{1}{4}\lambda_1 \left[v^2 + 2v\xi_\eta + \xi_\eta^2 + \zeta_\eta^2 + \xi_\eta'^2 + \zeta_\eta'^2 + 2\eta^+\eta^-\right]^2 \\ &+ \frac{1}{4}\lambda_4 \left[v^2 + 2v\xi_\eta + \xi_\eta^2 + \zeta_\eta^2 + \xi_\eta'^2 + \zeta_\eta'^2 + 2\eta^+\eta^-\right] \\ &\times \left[u^2 + 2u\xi_\rho + \xi_\rho^2 + \zeta_\rho^2 + 2\rho^+\rho^- + 2\rho'^-\rho'^+\right] \end{aligned} \tag{25}$$

Substituting (18) we get couplings of SIDM with the SM Higgs boson σ

$$\begin{aligned} L(\sigma,\zeta_\eta) &= \left[\frac{\sigma(x)}{\sqrt{\lambda_5^2 v^2 + \lambda_6^2 u^2}}\left(\lambda_1\lambda_5 v^2 + \frac{\lambda_4\lambda_6}{2}u^2\right) + \frac{H_1(x)\sigma(x)}{(\lambda_5^2 v^2 + \lambda_6^2 u^2)}\left(\lambda_1 - \frac{\lambda_4}{2}\right)\lambda_5\lambda_6 uv \right. \\ &+ \left.\frac{\sigma^2(x)}{2(\lambda_5^2 v^2 + \lambda_6^2 u^2)}\left(\lambda_5^2 v^2 + \frac{\lambda_6^2}{2}u^2\right)\right]\left(\xi_\eta'^2 + \zeta_\eta'^2\right). \end{aligned} \tag{26}$$

From Yukawa couplings, we see that our candidates do not interact with ordinary leptons and quarks [19].

$$\begin{aligned} \mathcal{L}^\eta_{Yuk} &= \lambda_{3a}\bar{Q}_{3L}u_{aR}\eta + \lambda_{4ia}\bar{Q}_{iL}d_{aR}\eta^* + \text{h.c.} \\ &= \lambda_{3a}(\bar{u}_{3L}\eta^o + \bar{d}_{3L}\eta^- + \bar{T}_L\eta'^o)u_{aR} + \lambda_{4ia}(\bar{d}_{iL}\eta^{o*} - \bar{u}_{iL}\eta^+ + \bar{D}_{iL}\eta'^{o*})d_{aR} + \text{h.c.} \end{aligned}$$

We see that the candidates for dark matter in this model have not couplings with all the SM particles except for the Higgs boson.

For stability of DM, we have to put mass of the SM Higgs boson is twice bigger mass of the candidate

$$\frac{1}{2}\lambda_1 v^2 + \frac{\lambda_4\lambda_6 u^2}{4\lambda_5} \approx \frac{1}{2}\lambda_2 u^2 + \frac{\lambda_4\lambda_5 v^2}{4\lambda_6} \geq -\left(\frac{\lambda_8}{4} + \lambda_{10}\right) w^2. \tag{27}$$

To avoid the interaction of DM with Goldstone boson, we have

$$\lambda_1 = \frac{\lambda_4}{2} \tag{28}$$

The *wrong* muon decay ($\mu^- \to e^-\nu_e\bar{\nu}_\mu$) gives a lower limit for singly charged bilepton $M_Y \sim 230$ GeV. Combining Eqns. (7, 8) with (9) we obtain the following relation: $u \sim v \approx 100 - 200$ GeV and $w \approx (500 - 1000)$ GeV.

The cross section for $hh \to hh$ (where h stands for ξ'_η and ζ'_η) with quartic interaction is $\sigma = \lambda_1^2/4\pi m_h^2$. The requirement on the quality $\sigma_{el}/(m_h[GeV])$ denoting the ration of the DM elastic cross section to its mass (measured in GeV) is that [9, 13, 20]

$$2.05 \times 10^3 \ \mathrm{GeV}^{-3} \le \frac{\sigma}{m_h} \le 2.57 \times 10^4 \ \mathrm{GeV}^{-3} \tag{29}$$

Taking $\lambda_1 = 1$ we get 4.7 MeV $\le m_h \ \le$ 23 MeV. The SIDM candidates interact with the SM Higgs boson by strength 0.65 if $\lambda_5 = \lambda_6 = 1$ and $u = v = 175$ GeV are taken.

Now consider the cosmic density of the h scalar given by [14]:

$$\Omega_h = 2g(T_\gamma)T_\gamma^3 \frac{m_h \beta}{\rho_c g(T)}, \tag{30}$$

where $T_\gamma = 2.4 \times 10^{-4}$ eV is the present photon temperature, $g(T_\gamma) = 2$ is the photon degree of freedom and $\rho_c = 7.5 \times 10^{-47} h^2$ with $h = 0.71$, being the critical density of the Universe. Taking $m_h = 4.7$ MeV, we obtain $\Omega_h = 0.18$. This means that the SIDM candidates do not overpopulate the Universe.

Recent analysis [21] shows that axions and majorons can be outcome in the 3-3-1 model. As well as the minimal 3-3-1 model, the considered model contains the Higgs bosons carried lepton number (scalar bilepton) and Higgs physics in the 3-3-1 models are much richter than that in the SM.

In conclusion, we have shown in this paper that the 3-3-1 model with RH neutrinos provides two Higgs bosons: one is scalar or CP-even and another is pseudoscalar or CP-odd particle having properties of candidates for dark matter. In difference with the previous candidate which introduced by hand, our self-interacting dark matter arises without impose new properties to satisfy all the criteria. Scalar dark matter candidates have been recently investigated in [22]. The DM stability could result from the extreme smallness of its couplings to ordinary particles, it is also necessary to impose a new symmetry: the Z_2 symmetry. Recently, astronomical observations suggest that 70% of the total energy of the universe can be associated to the cosmological constant [23]. Thus, the contribution of an exotic particle to dark matter would be about 30%. SIDM in our model do not interact with ordinary SM particle, exclude with the Higgs boson and estimation has shown that SIDM should be weak.

Financial support from Swedish International Development Cooperation Agency (SIDA) through the Associateship Scheme of the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy is acknowledged (H. N. L.). This work was supported in part by National Council for Natural Sciences of Vietnam contract No: KT - 04.1.2.

References

[1] M. S. Turner, Phys. Rep. 333-334 (2000) 619.

[2] N. A. Bahcall *et al,* Science 284 (1999) 1481.

[3] L. Wang *et al,* Astrophys. J. 530 (2000) 17.

[4] C. P. Burgess *et al,* Nucl. Phys. B 619 (2001) 709; M. C. Bento *et al,* Phys. Rev. D 62 (2000) 041302; M. C. Bento *et al,* Phys. Lett. B 518 (2000) 276; D. E. Holz and A. Zee, Phys. Lett. B 517 (2001) 239; V. Silveira and A. Zee, Phys. Lett. B 161 (1985) 136.

[5] S. Ghigna *et al,* Astrophys. J. 544 (2000) 616; J. F. Navarro *et al, ibid* 462 (1996) 563; B. Moore *et al,* Mon. Not. R. Astron. Soc. 310 (1999) 1147.

[6] B. Moore *et al,* Astrophys. J. 524 (1999) L19; A. Klypin *et al,* Astrophys. J. 522 (1999) 82.

[7] R. Davé *et al,* Astrophys. J., 547 (2001) 574.

[8] J. S. Bullock *et al,* Astrophys. J. 539 (2000) 517; R. A. Swaters *et al,* Astrophys. J. 531 (2000) L107; F. C. van den Bosch *et al,* Astrophys. J. 119 (2000) 1579; J. F. Navarro and M. Steinmetz, Astrophys. J. 528 (2000) 607; C. Firmani *et al,* Mon. Not. R. Astron. Soc. 315 (2000) L29; V. P. de Battista and J. A. Sellwood, Astrophys. J. 493 (1998) L5.

[9] D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84 (2000) 3760.

[10] N. Yoshida *et al.*, Astrophys. J. 544 (2000) L87.

[11] D. A. Buote *et al,* Astrophys. J. 577 (20020 183.

[12] J. P. Ostriker, Phys. Rev. Lett. 84 (2000) 5258; A. Burkert, astro-ph/0002409.

[13] J. McDonald, Phys. Rev. Lett. 88 (2002) 091304.

[14] D. Fregolente and M. D. Tonasse, Phys. Lett. B555 (2003) 7.

[15] F. Pisano and V. Pleitez, Phys. Rev. D 46, (1992) 410; P. H. Frampton, Phys. Rev. Lett. 69, (1992) 2889; R. Foot *et al,* Phys. Rev. D 47, (1993) 4158.

[16] R. Foot, H. N. Long, and Tuan A. Tran, Phys. Rev. D 50, (1994) R34; H. N. Long, Phys. Rev. D 54, (1996) 4691.

[17] H. N. Long and T. Inami, Phys. Rev. D 61 (2000) 075002.

[18] H. N. Long, Mod. Phys. Lett. A 13 (1998) 1865.

[19] H. N. Long: Right-handed neutrino currents in the $\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ electroweak theory. [hep-ph/9603258].

[20] B. D. Wandelt *et al, in* Marina de Rey 2000, Sources and detection of dark matter and dark energy in the Universe, pp. 263 - 274, [astro-ph/0006344].

[21] C. A. de Pires and P. S. Rodrigues da Silva, [hep-ph/0307253]; A. G. Dias and V. Pleitez, [hep-ph/0308037].

[22] C. Boehm and P. Fayet, *Scalar Dark Matter candidates*, [hep-ph/0305261].

[23] C. B. Netterfield *et al*, Astrophys. J. 571 (2002) 604.